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SURVEY PAPER

Morphological Computation in Haptic Sensation and Interaction: From Nature to Robotics

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Haptics, or the sense of touch, has played an important role in enhancing the versatility and capabilities of robots. Tasks involving unstructured or changing environments can significantly benefit from haptic sensation. The requirements of such sensing systems can be complex, however. Many designers have succeeded in using the morphological properties of the sensors themselves, such as geometry or material properties, to replicate or replace the functions of traditional computer control, reducing the burden on the central controller. This concept is generally referred to as *morphological computation* or *embodied intelligence* in the literature. This review will investigate the role morphological computation has played in haptic sensing and discuss potential future avenues of research. In the review, the concept of morphological computation will first be more rigorously defined. This is followed by an investigation into how nature has solved the problem of touch and a discussion of how such morphological principles could inspire design of similar systems in robotics. The state of haptic systems for display, sensing and interaction that utilise morphological computation is then surveyed. Finally, approaches to future research on morphological computation in haptics are discussed as well as some of the major challenges in this field.

Keywords: Haptics, Tactile Sensing, Morphological Computation, Biologically-Inspired Robots and Systems, Soft Materials

1. Introduction

Touch is meaningful. It helps humans intuitively assess characteristics of the surrounding environment without looking at them, thus enhancing stability and dexterity of object/tool manipulation, which is considered a crucial factor in human evolution. The human sense of touch can detect stimuli of various modalities, from roughness to temperature to pain [1,2].

The field of haptics deals with the sensation of touch and feeling in general. This includes both tactile phenomena, which comprise the interactions at the interface between two objects, and kinesthetics, which involve the intrinsic forces and positions associated with physically interacting with other objects. For example, when a human slides their fingertip along a surface, the tactile sensations are those experienced at the interface with the fingertip, such as pressure, force and texture. The kinesthetic sensations are those felt in the tendons and muscles that move the fingertip, such as the effort required to both press and slide the finger against the surface and the awareness of the pose of the finger. A robotic equivalent can be found in a robotic finger with a force/pressure sensor mounted at the tip. The tactile signals would be those from the

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force/pressure sensor itself and the kinesthetic signals would be those associated with actuator effort and joint angles.

In robotics, kinesthetic information is typically readily available from joint angle sensors, such as encoders, or monitoring motor force/torque. Tactile information, however, can be more difficult to monitor, given that contact can occur anywhere along the body of the robot and can involve both normal and shear forces of varying temporal frequency. As such, a significant recent focus has been on developing tactile sensing systems in robotics using various transduction methods, such as capacitive [11–14], optical [15], piezoelectric [16], resistive [17] and piezoresistive [18], for converting mechanical signals into electrical signals that could be detected by external circuits.

1.1 *Background*

There has been a great deal of research that addresses the development of efficient robotic haptic systems for better realisation of manipulation, grasp, interaction and so on [3]. Haptic systems fall into two general categories: *sensing* and *display*. Sensing, as is generally known, involves the measurement of some haptic signal and relaying it to some secondary system for processing. Display involves using a mechanical device to reproduce haptic signals such that they can be observed or experienced by a user. This is analogous to how a visual display allows a user to experience visual signals [4].

Mechanical interactions are one of the richest sources of information available during object manipulation or haptic interaction in general. Here, haptic *interaction* is used to encompass all possible ways in which a robot can affect—or be affected by—an external object which it is physically touching. Mechanical interactions are defined by phenomena such as stress/strain, vibration and friction. These stimuli are transferred from the point of physical contact to sensing elements through a physical medium. As a result, the sense of touch strongly depends on the *morphology* (the physical properties and shape) of that intermediate medium and the sensor's overall structure. Therefore, awareness of this relationship can facilitate the design of novel haptic sensing and display systems.

There has been much research that addresses the changing of either structure or mechanical characteristics in order to realise efficient haptic control interfaces (which include an element of haptic display) and haptic sensing systems. In spite of this, there has been relatively little research that explicitly considers morphological computation as a crucial *tool* in designing novel haptic systems (see Sections 4-6 for examples). While many concrete ideas on how morphological computation can facilitate control or locomotion have been examined (such as with passive-dynamic walkers—see [5–10]), there is less awareness of its use in haptics—especially in tactile sensing and general haptic interaction.

Furthermore, most recent survey papers have primarily focused on principles of transduction, electrical designs and data processing methods [3,19–21] rather than explicitly on how morphology could be exploited in haptics. Other reviews have examined manipulation in general [22] and specifically to do with soft robots [23]. Regarding the latter review, Hughes et al. investigated fabrication, design, sensing and actuation of manipulation systems in soft robotics (meaning robotic devices fabricated out of passively 'soft, flexible or compliant materials' [23]). There, some attention was given to how a system's morphology influences performance, but a detailed examination of the various ways in which this has been achieved in the literature was outside of the scope of the paper. Moreover, the field of haptics is not limited to object manipulation (as discussed above), thus warranting further investigation.

1.2 *Survey Focus and Organisation*

In an effort to look more broadly at haptic systems, this review will examine three primary areas of research. Firstly, it will investigate how morphological computation has been applied to create discrete sensing systems that employ morphological computation in order to enhance performance. Secondly, the review will survey robotic systems that rely on their morphology to produce novel behaviours with either reduced supervision from a computer controller or none at all. Thus, this review posits that the *computation* is a result of the haptic interaction (both tactile and kinesthetic) that occurs between the robot and its environment. Finally, the paper will explore how morphological computation can be used to not only capture haptic information (as done with sensors) but also reproduce it in haptic display systems. Throughout, this review will focus in detail on how deliberate selection of the morphology has produced novel or advantageous properties for the system's chosen application. This is done with the aim of drawing out design approaches and techniques that may be generalised to other endeavours in haptic system design.

To illustrate the focus of this review, Figure 1 shows how a typical haptic robotic system (including sensing, structure, actuation and display systems for maximum generality) can benefit from morphological computation. Figure 1 (a) shows a typical robotic system with haptic capabilities, but with no components utilising morphological computation. This same system is then re-imagined (in an idealised fashion) in Figure 1 (b) with some of the elements designed using techniques inspired by morphological computation. As can be seen, doing so allows many of the tasks once performed by the central computer control system to be offloaded to the morphology of the sensing, structural and display components themselves. This reduces the burden on the computer controller, allowing it to focus on other, high-level tasks. This review will examine the components which have been proposed in haptic robotics research that embed some element of computation in the morphology of the components themselves.

The review will begin by defining the fundamental concepts of morphological computation and its relationship with the field of robotics and haptics in **Section 2**. This will serve to introduce the concepts continually referred to throughout the survey.

As is often the case in engineering, several examples of morphological computation being utilised to great effect can be found in nature. Therefore, as an introduction to how morphology can concretely influence the quality of tactile sensation, **Section 3** will examine the design of tactile systems in nature. The morphology of these organs can inspire robotic designs. In contrast

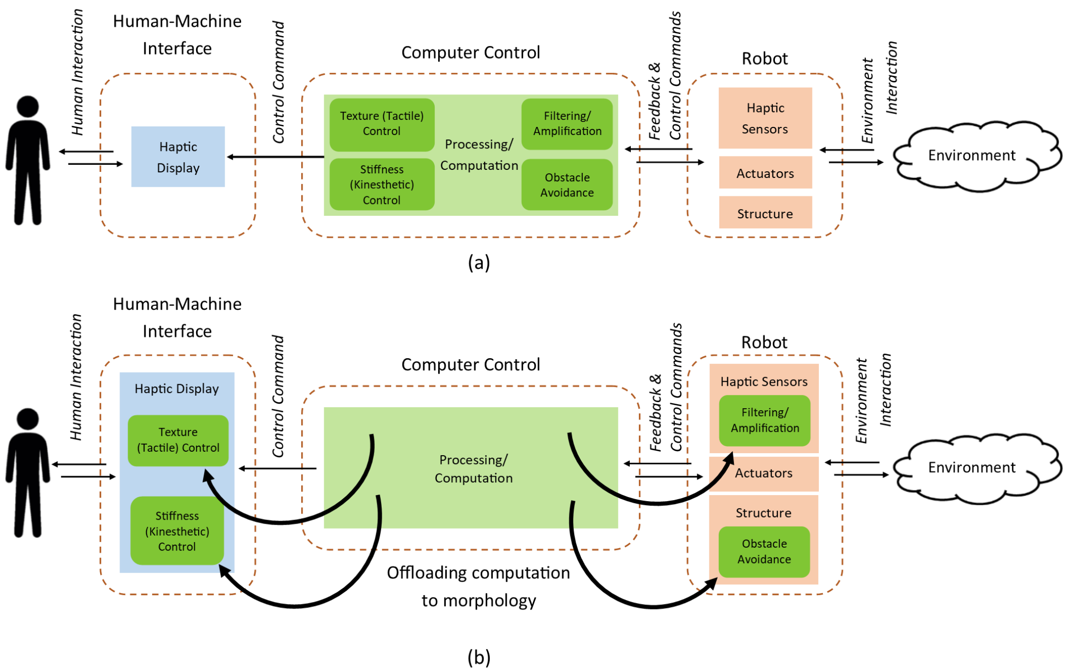

Figure 1. (a) An illustration of how information flows in an example haptic sensing and display system. (b) An idealised illustration of how embedding certain computational tasks in the morphology of the both the display and sensing components can offload some of the computational burden from the central computer control system to the components themselves.

to the survey in [3], where only humans' sense of touch was considered, we have extended the review to a broader range of animals for a more thorough assessment of how nature exploits morphology in tactile sensation. It is our intention that this will therefore inspire not only humanoid-inspired robots, but many other types of robotic systems.

With an understanding of how tactile sensing organs function in nature, **Section 4** will examine tactile sensors and sensing systems. Here, the focus will be on how researchers are taking advantage of morphological computation to create novel devices that rely less on digital signal processing. This will be split between systems that use passive morphology and active morphology. Passive morphology includes properties such as the compliance, geometry or transduction properties of the materials used. Active morphology looks at how adjusting passive morphology during operation can advantageously alter the sensor's performance.

Section 5 will then continue to look at robotic systems, but take a broader view and look at general haptic interactions. In contrast with the previous section that looked at sensing, the morphology of these designs enable them to *independently* adjust themselves without sending feedback to a central controller. This section will summarise how morphological computation can allow robots to perform novel tasks during interactions between the robot and its environment that are simultaneously kinesthetic and tactile. This section will not be limited to soft-robotic systems but will also include more 'traditional' rigid systems (see for example Sections 5.1 and 5.2).

Section 6 will briefly look at how researchers are using similar morphological computation techniques to reproduce tactile and kinesthetic information for humans in haptic displays. This is included to introduce how researchers are designing morphology to efficiently reproduce haptic information captured by robotic haptic sensing systems.

Finally, **Section 7** discusses possible directions for future research and proposes methods and tools for generating advanced haptic systems based on morphological computation.

2. Defining Morphological Computation in Haptic Interaction

The notion of morphological computation, used synonymously here with embodied intelligence, has been widely used recently [24] but its definition remains relatively obscure. Morphology can be considered as a combination between mechanical and geometrical characteristics. The computational element enters into it when these characteristics are utilised—either passively or actively—to generate desired behaviours in response to certain stimuli.

Generally speaking, then, morphological computation in haptics can be defined as any method or system that—either indirectly or directly—utilises the mechanical or geometrical characteristics of its own body to facilitate perception, locomotion and intelligence. This is also known as 'offloading computation from the brain to body'[24]. This concept is relatively familiar in the fields of biology and embodied intelligence, where it has been shown that some biological bodies behave 'intelligently' without supervision from the central nervous system (see Section 3). Using a similar approach in the design of robotic systems could equivalently reduce the computational burden on the central control system by distributing different functions in the sensing and actuating structures themselves.

An example of such a system can be found in soft robotic manipulators, as defined in Section 1. Such systems utilise morphological computation to facilitate control and perception without the need for a traditional controller [24]. Here, a soft manipulator's tendency to naturally deform in response to external forces will enable it to perform two functions. Firstly, it can passively conform its shape to that of an object in its path, thus removing the need to carefully control the system to both detect and avoid the obstacle (as also illustrated in Figure 1 (a)). Secondly, the shape and severity of the manipulator's deformation due to an external force is related to the nature of the force causing it, thus allowing the force to be measured (in theory). Hence, the soft structure can perform as both a controller in the first case and a kind of sensor in the second case.

To understand how the morphology of the soft manipulator in this example performs computation, it is useful to consider what would ordinarily be required of a classical, serial-link robotic manipulator to perform the same obstacle detection and avoidance. Firstly, the system would need to detect the obstacle using some set of sensors and compute the proximity of the object relative to some point(s) on the robot's structure (determining which point(s) is, in itself, also a computation). Secondly, it would need to compute what values of its kinematic variables would result in a pose which would allow it to avoid the obstacle. All of these tasks are achieved through some fusion of sensor information and prior knowledge/assumptions regarding the robot's shape which are built into computer software which calculates what parameters to use. In the case of the soft manipulator, all of these tasks occur as part of the system's intrinsic reaction when coming into contact with the object. In other words, since the morphology of the soft manipulator effectively produces the same results as a software computation, it is said that the morphology is performing the computation.

One consequence of this definition is that all elastic materials perform computation when deformed. While this may seem difficult to accept, we argue that this is no more problematic than the notion that a single transistor performs computation. In both cases, it is argued that the *context* and *arrangement* of these simple elements gives rise to the notion of computation. Hence, we recognise computation based on the behaviour of the system we observe. Therefore, if it is accepted that the classical manipulator's software performs computation, then since similar behaviour is observed in the soft manipulator, then the morphology is said to perform a similar role to that of the software and thus performs computation.

This example illustrates how adept selection of morphology (in this case, a soft structure) can decrease the complexity of a system by imbuing it with the ability to produce certain behaviours without the influence of an external controller. Here, this system's morphology is said to perform computation because it duplicates functions of complex control, such as obstacle detection, avoidance and surface following, which is traditionally accomplished using a computer/control software. In other words, while the commands given to the manipulator actuators do not necessarily change, the body of the manipulator is rearranging itself in response to coming into contact with the obstacle, thus performing actions which are equivalent to sensing and kinematics. It is therefore said that the 'control' which generates such behaviour (which is a form of computation) is 'embedded' in the morphology of the device itself and thus determines the behaviours/operations of the entire system.

Hence in general haptic interactions, a system performs morphological computation when, as a result of coming into contact with an object or the environment, the system uses its own morphology, the morphology of the environment/object or both in order to enhance perception or facilitate the task being performed. Particularly, this paper will explore how the morphology of a system can be designed to act as a mechanical computer and used to filter, amplify and generally condition signals or stimuli resulting from haptic interactions. This can produce significant quantities of high quality sensory information and thus facilitate the system's general perception of the environment. Much of the research presented here currently uses this design principle to perform only one of these functions (such as amplification, for example—see [13,14] and section 4.1.2). As more of such elements are coupled together in future designs (as was originally done in digital computing) there is potential to create full, *morphological* computing systems with several applications in haptic robotic applications, which are explored here.

A significant proportion of the haptic systems reviewed here have either entirely or partially soft structures. This is a natural consequence of the topic of morphological computation, rather than a deliberate focus on part of the authors. Rigid sensing systems or structures are—by definition—static. Therefore, rigid systems will produce little if no change in response to external stimuli and rarely (but not always) exhibit properties associated with morphological computation. On the other hand, it is not always the compliance of a structure that gives rise to morphological computation. Properties such as geometry (Sections 3.1, 3.2, 4.1.2), transduction

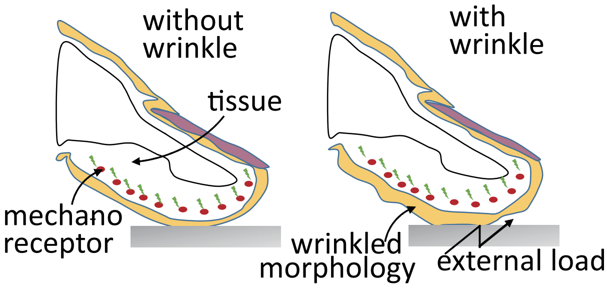

Figure 2. How wrinkled morphology relates to tactile perception. In tactile exploration, human skin and soft tissue act to mechanically 'filter' external excitations (such as texture, friction, and so on) before they are transmitted to mechanoreceptors. The response of these receptors is directly related to the perception humans have of the tactile stimulus. Thus, when wrinkle patterns form on the fingertip, the mechanical characteristics of this filter vary. The received response at mechanoreceptors therefore also varies, resulting in different tactile perceptions. Note that the wrinkle morphology is in addition to the morphology of fingerprints.

method (Section 4.1.3) and even environmental interactions themselves (Section 5.3) can be used to produce morphological computation in haptic systems.

3. Morphological Computation and Tactile Sensation in Nature

3.1 *Human Wrinkled Fingers*

The human sense of touch, including its underlying anatomy, has been long researched by scientists and psychophysicists. Humans' cutaneous sense of touch is characterised by a large number of mechanoreceptors situated at different depths underneath the outer-most layer of skin (epithelium). Stimuli originating at the contact interface between the skin and objects are transferred through skin and sub-skin organs to the location of these receptors. The spatio-temporal stress/strain caused by skin deformation stimulates these receptors, resulting in neural signals that define the perception of stimuli at the brain [1,38,39]. These receptors are mainly categorised into two types: fast-adapting (FA) receptors and slow-adapting (SA) receptors. FA receptors respond best to high frequency signals while SA receptors are more sensitive to stimuli that change slowly over time. These two types of receptors allow the sensation of touch to respond suitably to a wide range of input stimuli, such as contact location, vibration, slippage, and so on.

These perceptual abilities remarkably benefit humans when interacting with objects, such as grasping or manipulating them. As a result, there is also a great deal of research in the fabrication of tactile systems that mimic the same multi-modalities of human tactile perception. This would allow robots to efficiently process and recognise physical interactions with the outside world [3]. Most of this research attempts to replicate the systems found in humans. One approach is to fabricate sensing systems that have a similar spatial distribution of sensing elements to the mechanoreceptors found in humans [26]. Another approach involves large data processing/computation methods [29–33] which are analogous to human neural signal transmission.

In terms of using soft structures to perform morphological computation, one widely-known phenomenon that is considered to significantly affect sensing are the epidermal ridges (or papillary ridges) distributed on human skin [40]. In fact, there is a phenomenon that relates to an active morphological change in humans' tactile perception that has not been investigated thoroughly. Water-induced wrinkles on humans' fingers which appear after soaking in water is an example on how humans' soft skin changes its morphology in response to a change in environmental stimuli. These wrinkles reflect unbalanced strain in dermal layers [41], with the wrinkle pattern depending on the multilayered structure's geometrical and mechanical characteristics.

With regard to morphological computation, wrinkles cause a significant change in the skin's structure and the tribological interaction between wrinkled fingers and their environment. There is a hypothesis in biology that wrinkles may improve manipulation of wet or submerged objects

[42]. These authors claimed that wrinkles acted similarly to rain treads on car tyres, draining water away from the interface between the fingers of primates and objects they hold, thus increasing the success of manipulation. The fact that wet-induced wrinkles *only* appear at contact surfaces such as toes or fingers, where the locomotion or manipulation actions dominate [43] further supports this theory. Authors in [44] conducted psychophysical tests in which participants manipulated both dry, wet and submerged objects under two conditions: with and without wrinkled fingers. The time taken to transfer an object from one point to another while having to pass the object through a hole was measured. According to the paper, the results indicated that the transfer time of wet objects with wrinkled fingers was faster than without wrinkled fingers by 12 %. In contrast, there was little difference in the manipulation of dry objects with or without wrinkled fingers.

Even though the underlying mechanism is unclear, it is predicted that the morphological change induced by wrinkled fingertips improves tribological contact conditions [45] and tactile sensation in wet environments. Thus, it is feasible to assume that wrinkles vary the temporo-spatial responses of these mechanoreceptors and affect tactile perception (Figure 2). Therefore, skin (including epidermis, dermis, and soft tissue) can be said to act as a *filter* in transferring external stimuli to mechanoreceptors. This was investigated using a a bio-inspired sensor in [46–48] where it was shown that the presence of wrinkles improved the system's ability to detect high spatial frequency stimuli and slipping. Hence, this morphological change also improves sensing under wet (i.e. slippery) conditions. This conclusion may facilitate development of robotic *active* tactile sensing systems (see section 4.2 and 5.2) that can reproduce such a change in morphology to perform different sensing and manipulation tasks in varied environments without the presence of an external controller.

This concept differentiates itself from existing work that deals with active tactile *perception* [29–33], which relays individual tactile readings to a central controller which then computes how to reposition/reorient the sensor for the next reading in order to increase a classifier's confidence in identifying an object/surface. The active sensing systems suggested here refer to a physical sensor that, due to its specific morphological properties, will self-reconfigure in order to optimise performance in some task without the need for an external controller. This is akin to how humans do not *choose* to wrinkle their fingertips. Rather, these wrinkles are a result of the skin's specific morphology reacting to external stimuli and altering its properties in order to improve performance in a task. Early work done on 'active sensing' [27,28] had similar objectives to adapt how a tactile signal was processed in real time based on the nature of the signal. This, however, relied on a separate electrical or computational controller. Instead, here, the notion of active tactile sensing systems with respect to morphological computation have the ability to adapt to varying signals as an intrinsic property of the materials used in the sensor's structure. Research into replicating such functionality is still at an early stage and is discussed in more detail in Section 7.1.

3.2 *Crocodillian Bumps for Hypersensitive Touch*

Research into the sense of touch should not be limited to humans. In fact, some animals have surprisingly acute tactile perception with interesting structures/morphology that could inspire robotic research. While the human sense of touch is geared towards object grasping and manipulation, some animals have to heavily rely on tactile perception for localisation, sensing movement, warning of danger or communication. In this section, an example of how the morphology of crocodile skin benefits their acute sense of touch is introduced.

The armoured skin of crocodillia appears to be tough, rough and meant for protection rather than tactile perception. Surprisingly, authors in [49] discovered that the distribution of 'dome pressure receptors'—known as as ISOs (integumentary sensory organ)[50]—affords the species a tactile perception which is more sensitive than that of humans.

Figure 3 illustrates the morphology and distribution of mechanoreceptors inside the ISOs on

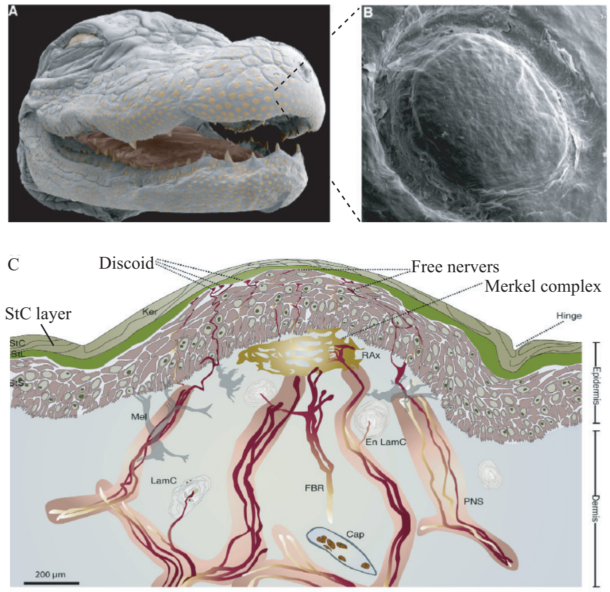

Figure 3. (A) A false-colour image showing the distribution of dome-structured ISOs on the jaw of the crocodiles. (B) A high magnification image of a single crocodillian ISO. (C) Illustration showing the distribution of the mechanoreceptors inside a single crocodillian ISO. (reproduced from [49])

the crocodile's jaw. In this animal, the average distance between adjacent ISOs on the jaw varies from 0.3 mm to 4.9 mm, with approximately 4200 ISOs distributed over this whole area [49]. In each dome structure, there is a dense network of mechanoreceptors distributed near the bottom layer of the animal's skin in the stratum spinosum (StS)—see Figure 3. Discoid receptors, characterised by enlarged terminals, are located right beneath the outer-most layer of skin. These receptors are connected to the Merkel complex, which is a key mechanoreceptor, and a network of axons. The most receptive nerve endings of the ISOs are located below the apex of the dome, inside the StS layer, where many axons converge. This morphology can account for the acute tactile perception of crocodiles, which has been investigated earlier in [51] and recently reported in [52] as containing 'touch receptors tuned specifically to pressure and vibration, plus a host of raw nerve endings'. The dome-like structure, moreover, is considered ideal for channelling any deformation caused by stimuli toward its geometrical centre, regardless of the direction of the stimuli. It is no coincidence, then, that the Merkel complex is located at this geometrical centre, as this maximises the range of stimuli to which it is exposed.

In order to investigate the responsive field of these ISOs, authors in [49] conducted thorough experiments on a large sample of Nile crocodiles. Here, the mechano-sensory thresholds were recorded using standard instruments known as von Frey hairs [see 53]. The lowest thresholds were found in ISOs around the front tip of the jaw, surrounding the teeth. Here, a single ISO was responsive to a 0.078 mN indention force which is much lower than that of humans [54]. In addition, regarding the response of rapid adapting receptors, experiments revealed that RA units could respond to frequencies over 350 Hz. This extreme sensitivity, a product of the specialised morphology of ISOs and the distribution of internal mechanoreceptors, was said to help crocodiles localise objects underwater, such as prey or potential predators [52]. Other hypotheses considered crocodilian ISOs as pressure receptors (osmoreceptors) [55]. The morphology of these ISO dome structures in crocodillian tactile organs maximises the available information which can be inferred from a single stimuli. This can give hints for designing equally effective *passive* tactile sensor structures.

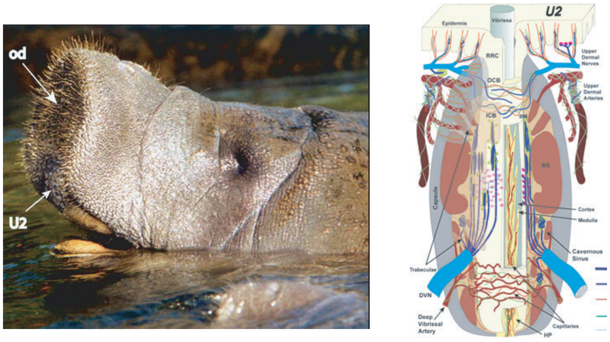

Figure 4. Tactile hairs (vibrissae) on the face of manatees and the anatomy of the capsule-like tissue with a distribution of mechanoreceptors (reproduced from [56]).

3.3 *Tactile Hairs*

Some animals rely on tactile perception to compensate for reduced visibility, particularly in aquatic environments. For example, manatees are almost blind but possess highly receptive sensory fields for navigation and detection of prey underwater [56]. Manatees' detection of mechano-sensory stimuli is reported to be due to the morphology of *vibrissae*, or tactile hairs, distributed all over their body. According to authors in [57], manatees have a large portion of their vibrissae distributed around their face (about 2000) compared to their entire body (about 5300). This is different to most other mammals, which only have vibrissae on face (rats' whiskers, for example). Differing from the structure of ordinary hair, follicles that are accompanied with vibrissae have 'blood sinus, dense connective tissue capsule, and variety of mechanoreceptors', known as follicle-sinus complexes (FSCs) [56]. The tissues of FSCs, buried underneath the skin, have a noticeable capsule-like shape which can accommodate a wide range of nerve endings [58]. This includes Merkel endings, novel trabecular endings and tangential endings, all of which have low mechano-sensory thresholds. This results in highly a sensitive and large receptive field on the manatee's face (Figure 4). Thanks to the dense population of Merkel endings inside FSCs, it is hypothesised that manatees are able to detect the *direction* of follicle deflection [56], a perception of which human hairy cutaneous skin is incapable.

The vibrissae on the face of manatees have the highest density of axons with a total of 100,000 axons innervating all accommodated FSCs, making them extremely sensitive. Additionally, the posture of vibrissae is actually *actively* controlled by facial muscles around the mouth [59]. When approaching an object, manatees attempt to change the shape of the their mouth so that vibrissae extend outward, like a physical array of antennae for tactile investigation/exploration. Interestingly, bristles around the mouth are utilised for grasping and manipulating objects that are ingested orally, known as *oripulation*. As a result, given the density of mechanoreceptors and nerve endings, by changing the posture (i.e. the morphology) of vibrissae, both tactile exploration and oripulation abilities are enhanced simultaneously.

3.4 *The Star-Nose as a Tactile Organ*

The star-nosed mole is a mostly blind animal that uses its ultra-sensitive snout to 'see' the surrounding environment and search for prey [60]. Each snout has 22 tentacles (or rays) that are sensitive to touch and can hunt or grab prey such as insects or worms. These tentacles, therefore, have similar functionality with manatees' vibrissae. While manatees receive tactile stimuli indirectly via the movements of vibrissae, the star-nosed mole's tentacles possess an ultra-high density of mechanoreceptors distributed under its skin which are directly stimulated by the environment. Authors in [61] have examined how these animals use their nose and found that the surface of each tentacle is covered in dome-like structures known as *Eimer's organs*. The Eimer's organs, illustrated in Figure 5, have a *column of central free nerve endings* (CF)

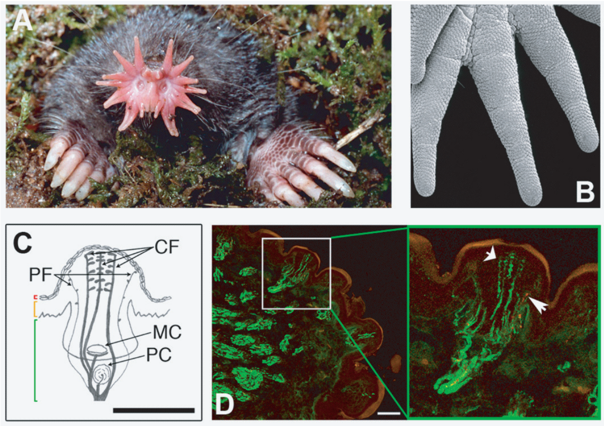

Figure 5. Star-nosed moles with rays covered by 30,000 domed Eimer's organs (reproduced from [60]).

starting just beneath the outer-most layer of skin. Distributed around this column are finer peripheral axons (PF). It also contains classical mechanoreceptors such as a Merkel cells (MC) and Pacinian corpuscles (PC). This organ's structure results in high stimulation of nerves from external stimuli and creates a highly receptive and sensitive organ.

There are a total of 30,000 domed Eimer's organs on the snout of the star-nosed mole compared to only 17,000 touch fibres distributed over the entire human body. In addition, there are more than 100,000 axons distributed on a 1 cm diameter area of the snout, making this snout one of the most sensitive tactile organs among animals. Similarly to manatees, the star-nosed mole can *actively* move their tentacled snout, especially the two rays at the bottom-centre of the star toward an object of interest in order to accomplish tactile exploration. As a result, in order to attain a hypersensitive tactile perception, animals like manatees and star-nosed moles not only need to possess tactile organs with special morphological properties—such as high densities of nerve endings and mechanoreceptors—but *active* tactile organs. This, as a result, allows them to rely on their sense of touch to perform complex tasks where humans would rely on their visual sense.

As the result of evolution, many animals have developed a renowned sense of touch with remarkable sensitivity compared to that of humans. Examples given in this section are just a few typical creatures that possess tactile organs with special morphology. For example, 'touch spots' found in frog skin also possess low mechano-sensory thresholds (i.e., a high receptive field). These were physiologically characterised in [62]. Authors in [63] found morphological protruding centres in some snakes' cutaneous sensing organ. The nature of these tactile organs could bring great hints for development of tactile devices in robotics research.

4. Tactile Sensing and the Role of Morphology

In sensor design, selection of appropriate morphological properties is not a new idea. Designing the morphological aspects of the sensor such that the appropriate sensitivity and range are achieved is common place in many applications. For example, a common force sensing technique, a cornerstone of haptics, involves a strain gauge measuring the strain of a beam. The dimensions and elastic properties of that beam determine the range of forces and sensitivity of the force sensor. Thus, depending on the desired properties of the sensor being designed, engineers will choose the beam material and its geometry in order to create a sensor which will provide sufficient accuracy and resolution. This is the most basic example of how morphology influences sensor performance.

Tactile interactions tend to be more complex than simple force measurement, as interacting with other surfaces (i.e. the act of measuring them) may change the surfaces' properties. Addi-

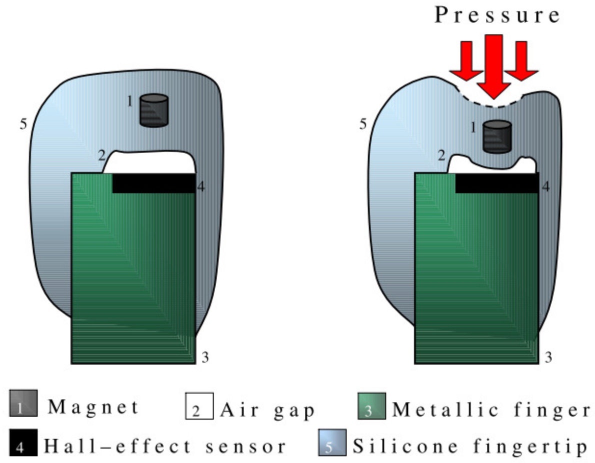

Figure 6. Magnetic sensor relying on the deformation of a soft medium to infer applied force (reproduced from [66])

tionally, there is a large range of information types (texture, friction etc.) that are desirable to measure, further complicating the task. Therefore, more is demanded of sensors that measure tactile information. As a result, many tactile sensor designs need not only consider how their morphology will influence the sensor's properties, but also consider how those properties will influence the surface being measured. Given the computational difficulty associated with compensating for this using a traditional controller, morphological computation offers a technique to allow the components *themselves* to compensate for this complex interaction, thus offering advantages over traditional sensor design approaches. In this section, the computation exhibited by the designs examined will generally be to either amplify, differentiate, sum/integrate or filter a signal. While these are not particularly complex computations, they are essential. Furthermore, the complexity of even the most intricate computing systems generally emerges as a result of the interconnections between many simple elements. Hence, the works discussed here can be viewed as small elements of what could be larger morphological computational systems (see Section 7 for a more detailed discussed on this topic).

This section will provide an overview of how morphological computation is achieved in tactile sensing. This can be split into two main groups:

- Passive morphology, which cannot be altered actively. This is separated into three subcategories: compliance-based, geometry-based and transduction-based designs.
- Active morphology, which allows for the morphology to be actively changed in order to alter the properties of the sensor at will.

Then, an overview of how some designs have utilised novel geometries to enhance the capabilities of their tactile sensors will be provided. Finally, the paper will describe designs which exploit the intrinsic transduction methods of a given materials to measure different types of tactile stimuli.

4.1 *Passive Morphology*

4.1.1 Compliance-Based designs

Many tactile sensors rely on the compliance of some intermediate material between the sensing element and the target surface in order to extract information. An early idea of utilising the compliance of a tactile sensing element was introduced in a paper by Clark [64]. Here, he discusses so-called *compliance matching*, wherein a compliant structure is situated between the sensing element, assumed rigid, and external forces. By sensing the shape of this compliant medium, high resolution sensors may be used to infer the forces acting on that medium.

This idea has since been employed in designs using various transduction methods. Tactile sensors that rely on the compliance of an intermediary medium have been developed using various sensing methods such as magnetic [65–68], ultrasonic [69], capacitive [11], fluidic [70–72], piezoelectric and piezoresistive [73] and optical [74,75] methods. These all endeavour to measure applied forces by measuring the deformation of the compliant medium, similarly to Clark's initial concept. In all cases, material compliances such as the Young's modulus or Shore hardness contribute directly to the sensor's performance. As with the example given at the beginning of this section, the natural tendency for the soft material to deform in some predictable way allows the sensor to estimate the contact forces. This in itself is not new, but all of the examples above are notable for taking the fullest advantage of their compliant structure to achieve good resolution and accuracy in a relatively small package. The sensor in [75], for example, is smaller than a human finger-tip and has 9 discrete sensing points and was intended to provide minimally invasive surgical robots tactile feedback (see Section 6). Generally speaking in these designs, stiffer materials will be more sensitive to higher frequency input stimuli, while softer materials are more sensitive to low-magnitude and low frequency stimuli. Hence, these materials perform the same computation as a electrical or digital filter.

4.1.2 Geometry-Based designs

A number of designs continue to rely on a compliant intermediary medium, but focus more on finding optimum geometries to facilitate measurement. Further to relying on correct material stiffness selection, the design in [75] uses channels of reducing cross-sectional area to amplify displacement of a compliant medium as it is pressed through the channels by an external force.

Micro-pillars of increased rigidity have been embedded in compliant/viscous media in order to enhance sensor sensitivity by transmitting forces to the sensing element more effectively [76–78]. This is due to the micro-pillars acting as lever arms and amplifying the moment/forces seen at the sensing element. Some designs have realised this as small, bump or hair-like structures on the surface of the sensor to enhance sensitivity to small texture changes [80,83]. Authors in [83] built a sensor which could read Braille characters, neatly demonstrating the wealth of information available to robots through tactile interactions in general. Thus, the computation performed here is equivalent to that of an amplifier. Furthermore, as discussed in Section 3.1, this emphasises how adept choice of morphology can create high-performing sensors in small packages.

The use of compliant hemispheres is also popular due to their mathematically predictable deformation [79–82] and, as found in the ISOs of crocodiles (see Section 3.2) their ability to channel the effect of deformation to a central point, regardless of the direction of the stimulus. In terms of the computation being performed, this would be equivalent to summing or integrating a signal over an area. This is particularly useful for detecting both normal and shear forces [81]. These forces are critical when performing grasping as they will allow the robot to estimate the object's weight from the shear measurement while regulating the normal force applied by the gripper. Furthermore, this well defined geometry allows a variety of surface features to be discerned, such as sharp edges or other geometrical features [79,80]. Liu et al. [82] used soft, rubber robotic fingertips in the shape of an ellipsoid to extract the locations, directions and magnitudes of a contact force using a single 6-axis force/torque sensor. As was seen in Section 3.2, the dome-like/ellipsoid geometry of the soft fingertips maximised the amount of information attainable from measurements taken at a single point. This was in turn used to automatically follow the surface of an unknown object and extract tactile information such as the surface friction coefficient and object geometry.

Structural asymmetry was utilised in [12] to reduce the error in angular deformation detection in a capacitive tactile sensing array. The built-in asymmetry reduced the impact of electrode misalignment induced either during fabrication or during operation. Sensitivity of such capacitive arrays was improved significantly through the fabrication of micro-structured dielectric materials in [13] and [14] (see Figure 7). The work in [14] employed a two part geometrical design. Here,

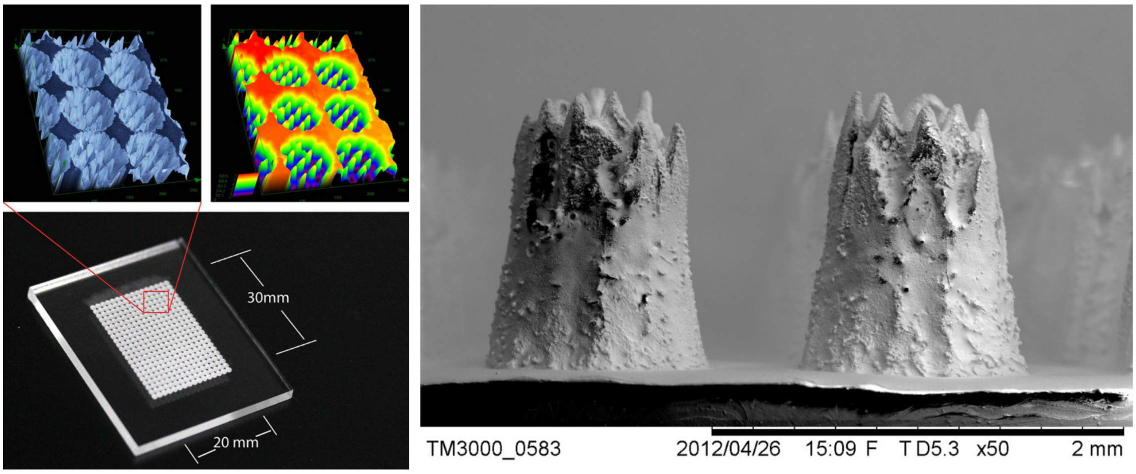

Figure 7. Microstructured geometry able to greatly enhance the sensitivity of capacitive sensors. Left: The mould which was used to cast the flexible dielectric material used in the capacitive sensor. Right: The smaller structures situated on top of the larger conical structures. (reproduced from [14]).

conical structures of a height of 800 µm were combined with even smaller cones of a height of 100 µm, situated on top of the larger structures (see Figure 7, right). The combination of features of different scales meant that for small forces, most of the change in sensor output would be due to deformation of the small features and be highly sensitive; for larger forces, the effect of the small structures deforming would be insignificant compared to that of the large structures. As a result, this combination of feature geometries allowed for very high resolution for forces under 1 N while simultaneously allowing a large range of measurement up to 15 N (albeit at lower resolution). Here, the asymmetry is acting simultaneously as an amplifier and a filter. Furthermore, this structure adaptively adjusts itself to optimise its performance based on the nature of the input.

4.1.3 Transduction-Based Designs

Some methods of transduction are better suited to specific types of stimuli, whether that be high or low frequency or only sensing the rate of change of an input as opposed to its magnitude. This echos the presence of SA and RA receptors found in many biological tactile systems, as discussed in Section 3. Researchers have attempted to mix multiple transducer types in a single sensor in order to capture several aspects of a signal.

A combination of piezoelectric elements and strain gauges were used in [84–87] in order to facilitate secure grasping (see Figure 8). The strain gauges were primarily used to measure the normal forces exerted by the grasper, while piezoelectric polyvinylidene fluoride (PVDF) elements were able to detect high frequency signals produced by objects slipping. The technique was applied in order to allow the gripper to grasp objects while their weight was changing. As the object increased in weight, the ability to detect the instantaneous slipping of the object (a high frequency stimuli) was primarily due to the PVDF elements. Grasping strength would then be increased in order to prevent the object from falling, where the strain gauges would primarily detect the overall change in stress (which was proportional to grip strength). Hence, the two transduction techniques were akin to the two types of mechanoreceptors discussed in Sections 3.1 and 3.2.

A similar approach, where different transduction elements were used to measure signals in different frequencies was developed in [88] in order to sense different flow regimes in water. This took direct inspiration from the SA and RA receptors found in crocodiles discussed in Section 3.2 and was capable of detecting different flow regimes. Piezoelectric elements were again used to sense rapidly changing signals but instead of strain gauges, piezoresistive elements were used

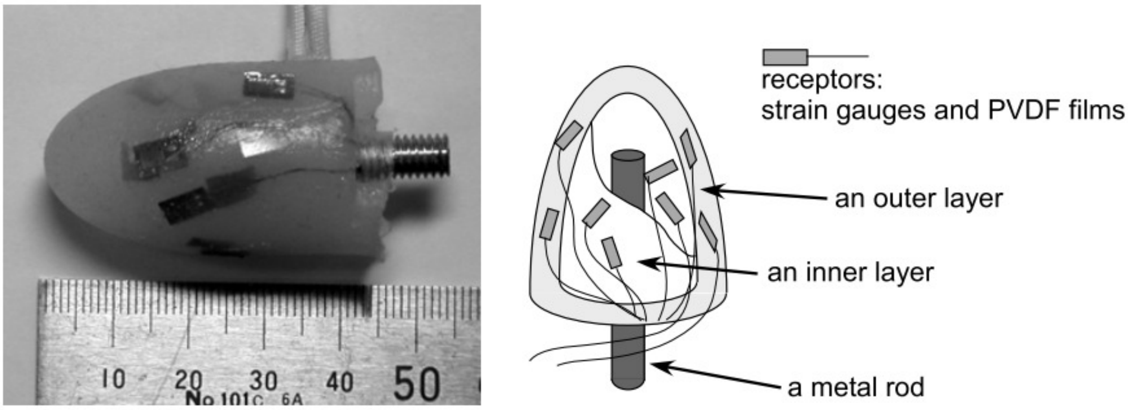

Figure 8. Fingertip sensor using a combination of strain gauges and PVDF elements (reproduced from [86]).

to detect steadier signals.

In summary, each transduction method can be associated with a specific type of filter, such as a band-, low- or high-pass filter. In some cases, it could be argued that differentiation is being performed by some of the transducers, such as the PVDF elements in [84–87].

4.2 *Active Morphology*

Actively changing sensor morphology in order to adapt to different stimuli is a relatively new concept. It does, however, tend to involve a significantly more complex design. While the design process may be more demanding, the expanded capabilities of such a sensor can be argued to justify this added complexity.

Work in [89] demonstrates a system which could theoretically sense both the stiffness and temperature of a target object. This uses familiar sensing techniques—such as measuring the deflection of a beam—in order to estimate the force exerted on the target object. The novelty here was that the system would automatically *manufacture* the beam *in-situ*. The beam, consisting of hot melt adhesive, was extruded on demand from a device mounted on the end of a robotic arm. The robotic arm then brought the beam into contact with a target object and the deflection of the beam was measured with a computer vision system. This was then used to estimate the contact force. The dimensions of the beam could potentially be changed on the fly in order to adjust the sensitivity and range of the system, thus allowing users to fabricate a sensor to fit a much wider range of sensing tasks. The interesting idea here is the concept of a kind of *self-reconfiguring* system which, by some adaptation algorithm, could change the shape of its sensing element (the beam) and thus alter the properties of the sensor.

This concept of active morphology was refined in [46–48] where an analogue of a human fingertip was fabricated. Inspired by how human fingers become wrinkled when exposed to water (see Section 3.1 and Figure 9), the texture of the sensor's 'skin' could be changed at will from relatively smooth to an undulating texture. The design used embedded strain-gauges in a soft material. Chambers situated underneath the strain gauges were inflated with air, causing parts of the sensing surface to bulge. Thus, artificial wrinkles were created in the sensor's skin. Experiments showed that the sensor was significantly more sensitive to dynamic sliding actions with high frequency components. Hence, it was possible to alter the sensor's frequency response at will in order to improve the output to a specific stimuli, demonstrating the notion of morphology acting as a *filter* as discussed in 3.1.

5. Haptic Interaction and Morphology

Utilising interaction is critical to taking full advantage of haptic information. Section 4 described how a great deal of information about objects and the environment is available through tactile sensing. The sensing systems discussed so far, however, need to be mounted to some robotic device which actually brings the sensors into contact with the environment in the first place. Furthermore, information from this sensor must still be processed by some central computer controller in order to react to the information received. As discussed in Section 3.4, an *active* tactile exploration of the environment is key to taking full advantage of the information available through the general haptic interaction. Hence, creating actuation or general design techniques which allow robots to interact with their environments in specific ways without the need for a computer controller is crucial to achieving this. This section will demonstrate how carefully considering the morphology of a system can imbue robots with the ability to independently react and adapt to their environment. This adaptation is the result of interacting with the environment and achieved without discrete sensing or direct computer control. Thus, the familiar sense-process-react loop used by robots (and animals) is embedded in the robot's morphology itself. As a result, this section will not examine *integration* of sensors with robotic systems, but rather how systems can be designed from their inception to simultaneously act as both sensor, structure and actuator.

There are, broadly speaking, three primary types of morphological computation which are being employed to assist haptic interactions: passive compliance, active compliance and environmental interaction. Interacting with the environment is in some ways a combination of several other factors—including the previous two categories. It does, however, set itself apart as in that it involves a deliberate identification and selection of interactions that will facilitate completing the desired task. Passive and active compliance designs do obviously interact with the environment, but the works discussing such designs tend to view these interactions as *acceptable* rather than *intentional*. The following sections will expand on these three types of morphological computation and describe some of the advantages and capabilities of each approach.

5.1 *Passive Compliance*

A number of reviews have looked at the development of soft robotics in general [91,92] and will not be examined in detail here. Such soft devices utilise the passive compliance built into their structures to perform tasks which conventional robots would find challenging or even impossible. Examples of such tasks include safe human-robot interaction, especially in the medical field where safety is of paramount concern [91]. Compliance can lead to rapidly adapting systems that adjust to disturbances without the need for a traditional sensor-controller-motor system [92]. Hence, in such compliant systems, the interaction *itself* is directly responsible for altering the characteristics of the system. Popular examples of such a soft robotic system in can be found in [93–96] and were discussed in [23], where a soft universal gripper will conform its shape to an object after being pressed onto it, enabling it to grasp a wide range of objects. Thus, the adaptation is a direct response of the material to the disturbance from the environment. This avoids the need for on-line computer computation (as here, this is performed by the morphology) and creates rapidly adapting mechanisms with complex behaviours [92].

An excellent example of this principle of rapid adaptation was shown in [98] where the ability of a goat hoof to remain stable in highly treacherous terrain was explored. Here, a passive device inspired by the structure of goat hoofs was created. It was shown that, with the assistance of passive springs and specially chosen geometry, the mechanism was able to significantly increase the energy required to slide the hoof, compared to a simple rounded shaft. Thus, it was shown that the geometry and compliance of the mechanism improved the grip interaction between the hoof and the surface, preventing slip. This involved reconfiguration of the whole mechanism as a result of the surface (i.e. tactile) interaction and is therefore haptic—not only tactile—

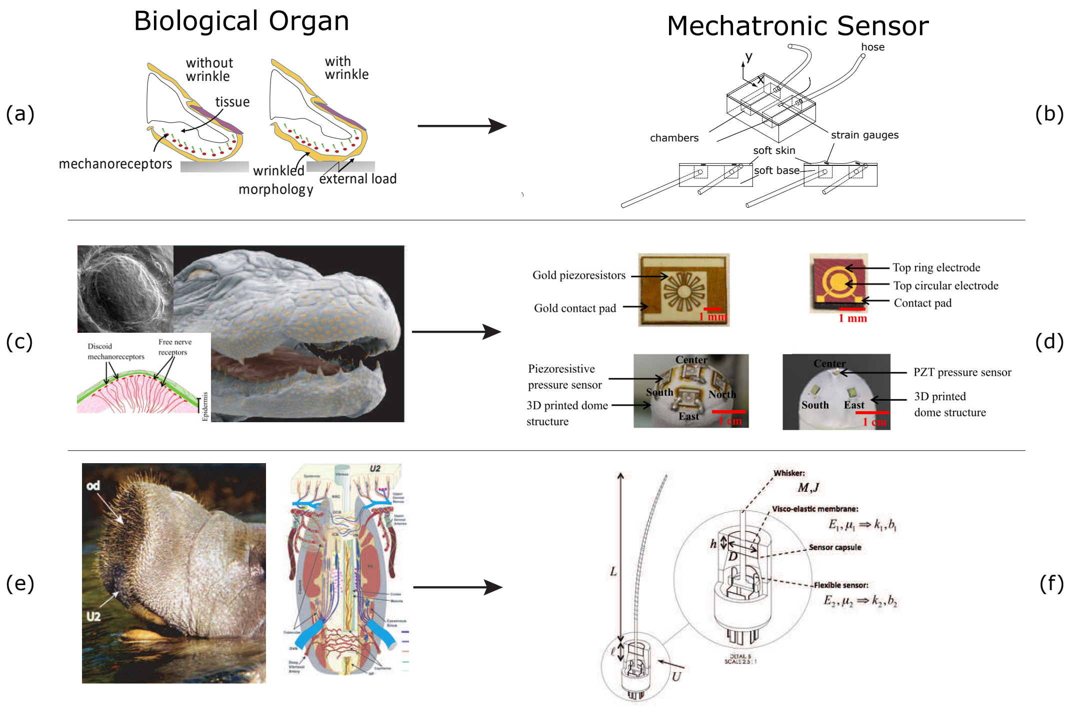

Figure 9. Illustration of how some sensors use similar morphology to that found in nature. (a) - (b) How a human finger tip changes its geometry in response to becoming wet and the tactile sensor inspired by this change in geometry (reproduced from [46]). (c) - (d) The mechano-receptors found in crocodiles and the sensors that use different transduction methods in order to replicate the ability to sense pressure changes at both high and low frequencies (reproduced from [49]). (e) The tactile hairs found on manatees (reproduced from [56]) and (f) the sensor inspired by this function (reproduced from [97]).

in nature. Friction and slip are inherently difficult phenomena to model [99], so this design clearly exemplifies the advantages of 'offloading' some of the computational burden to passive components.

5.2 *Active Compliance*

While compliance can be utilised to rapidly adapt to different environments, this is not always desirable when the task involves exerting a force on the environment. By design, soft structures deform rather than transmit force. This is of particular concern in surgical manipulators which, on the one hand, need to be soft to avoid damaging tissue when accessing the surgical site, but on the other, need to be stiff enough to make incisions. In response to these contradicting requirements, researchers have examined techniques for actively changing the stiffness of compliant devices [100].

The most direct approach to actively controlling stiffness relies on using antagonistic actuation, where two actuation systems exert opposing forces. By choosing the magnitude of each respective force, the apparent stiffness of the structure or joint can be varied. This technique was employed in [102] in a continuum manipulator, where tendons driven by DC motors would pull against a pneumatic actuation system. The system developed in [103] only used tendons acting against each other and allowed for highly accurate control of the stiffness in all three dimensions and generalised their approach to any tendon driven system with a flexible backbone.

Controlling stiffness has also been shown to influence the effectiveness of robots performing haptic tasks such as palpation. This is considered a haptic interaction and not just a tactile interaction because both the kinesthetic information associated with the material's stiffness and the direct pressure/force applied to the sensor must be considered. In Sornkarn et al. [109–111], using antagonistically actuated stiffness control, it was shown that the accuracy of detecting a hard nodule embedded in soft tissue (analogous to a tumour) can be optimised with respect to the depth of this nodule by varying the stiffness. The timing and degree to which stiffness was altered was based on an on-line decision-making algorithm employed during palpation. This further illustrates the importance of designing suitable interaction platforms for haptic sensing systems. The sensor used in the tests (a 6-axis force/torque sensor) was not altered during the trials, but the morphology *surrounding* it changed its ability to detect stimuli. Hence, the interaction between the soft tissue analogue and the stiffness of the robot demonstrated morphological computation.

Granular or layer jamming have also been of particular interest to researchers in changing the stiffness of compliant structures, particularly with continuum manipulators. In general, this relies on friction between small particles or sub-structures increasing the apparent stiffness of a manipulator. A jamming robotic hand in [34] utilised granular jamming to change its stiffness on demand and to facilitate grasping of a wide range of objects. Work in [104] and [105] uses small, interleaved surfaces to create friction. The surfaces are housed inside of a sealed pressure chamber with a flexible outer skin. When pressure in these chambers is reduced, the flexible skin contracts around the interleaved surfaces, causing them to press together and friction to increase. A similar idea was developed in [106], except here a braided mesh structure was used to compress the interleaved layers. Structures inspired by fish scales appear in [107] where a series of small structures are coiled around a soft continuum manipulator. A tendon running through all of the coiled structures is used to increase contact force between adjacent coil segments, thus increasing friction and the overall stiffness of the structure.

Zuo et al. [108] developed a novel set of interlocking structures which increased the stiffness in a similar fashion. This was deployed in a Natural Orifice Endoscopic Surgery (NOTES) device and proven in an *in-vivo* pig animal test. The device was guided through a natural orifice in the flexible mode, thus avoiding damaging surrounding organs. When at the operation site, the rigid mode was engaged and tools were deployed. The enhanced rigidity allowed the device to increase its stiffness roughly four-fold [108] and allowed a partial gastrectomy to be performed. This demonstrates how controlling the stiffness of an instrument can enhance the range of interactions it is able to perform.

5.3 *Interacting with the Environment*

Haptics studies how robots and the environment interact, but—for the most part—has tended to consider the robot as isolated from the environment. Morphological computation changes this paradigm by *coupling* the robot and the environment. That is, the robot influences the environment and vice-versa. While this can be said of all robotic manipulation systems, the examples explored in this section generally either allow the environment to significantly change the configuration of the robot itself or use the environmental constraints in a novel way to further enhance task performance. This also distinguishes itself from control techniques that employ a model of the environment by primarily relying entirely on the passive properties of the robot's morphology rather than a digital/analogue controller. An example of a robot that uses an off-line model of the environment to determine its control can be found in the bipedal robot developed in [8,9]. Here, it was found that a parameter of the simple controller used would automatically converge towards an optimum value as the robot took more steps without the need for any sensor feedback. In other words, as the robot and environment interacted, the dynamics would self-adjust to stabilise the system. While this is mainly an achievement in dynamics research, the principle of a system using the environment to adapt towards some optimal configuration can be extended to haptics and is certainly worth investigating.

The ability to rapidly adapt to different environments that passively compliant structures exhibit can be further harnessed to produce even more complex behaviours. These involve deliberate and specific interactions with the robot's environment that allow it to complete tasks more effectively. In other words, the additional constraints, if used correctly, can assist in performing an action. As discussed in [90], environmental constraints can be used to guide or shape the ac-

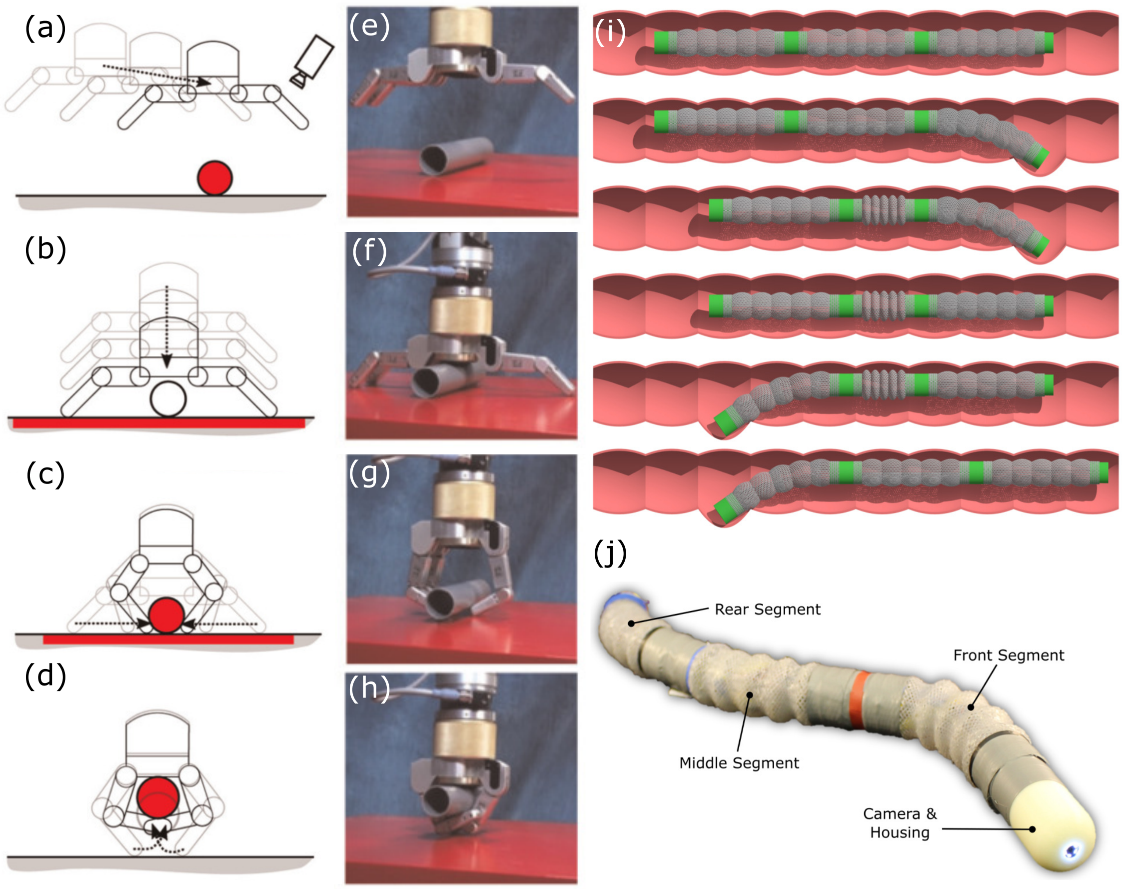

Figure 10. (a)-(h): Illustrations and photographs of a robot utilising the constraints imposed by the environment to achieve a more stable grasp (reproduced from [112]). Here, the grasper uses the surface on which the object is resting to guide the gripper towards a stable grasping configuration. This demonstrates how it is possible to use pre-existing constraints to simplify the grasping task. (i)-(j):The worm-like robotic endoscope. (i): The locomotion technique utilised by the robotic endoscope which relies on selectively jamming itself inside of the colon (reproduced from [113]). (j): A fill view of the robotic endoscope (reproduced from [113]).

tions performed by a grasping robot. This offsets some of the computation needed to compute a stable grasp and can therefore improve performance of relatively simple graspers. Here, then, the morphology of the environment, object and robot can be made to interact in order to produce new, more complex behaviours.

Obstacle interaction is used in [112] to improve grasping stability, albeit with a rigid link manipulator. Here, the surface on which an object is resting is used to guide the grasping process. Rather than attempting to compute the most stable grasp offline using only the manipulator, the contact points already in place due to the environment (i.e. a rod laying on a flat surface—see Figure 10) are incorporated into the grasping strategy. In many cases, such environmental contact points are inherently stable as long as the object to be grasped has come to rest and the environment is stable. It is therefore highly advantageous to take advantage of these stable constraints as the morphology of the environment serves to naturally guide the grasping process. The computational burden is therefore drastically reduced. Essentially, the morphological computation for this process is shared by the environment and the device itself.

Environmental constraints are exploited in [113] in order to propel a worm-like endoscopic robot through the human colon, a highly torturous and unstructured environment. The robot consists of three segments connected in series. The two end segments can contract and bend in any direction while the middle segment can only contract. The locomotion principle relies on the fact that the human colon is roughly tubular in structure. Therefore, by sufficiently bending either of the end segments, they 'jam' inside of the colon and create an anchor point.

Selectively creating anchor points and extending/contracting the middle segment will thus allow for a locomotion technique shown in Figure 10 (i). By using the environment, the design is allowed to be simplified as additional systems are not required for turning or orientation of the end segment. Additionally, each segment is passively compliant and can therefore conform to the highly irregular shape of the human colon. Thus, the device is highly adaptable to the torturous path and varying diameter of the human colon without the need for on- or off-line computation of optimal configurations. Thus, again, much of the 'computation' is performed through the natural interaction between the robot and environment.

Inspired by the techniques found in nature discussed in Section 3.3 and 3.4 (see Figure 9), a system for navigating an environment with unknown obstacles was proposed in [114], [115]. Here, whiskers were used to sense obstacles and perform navigation. These were mounted on a mobile robot and it was shown that certain whisker morphologies performed better than others when tasking the robot to explore an unknown environment and simultaneously avoid obstacles. Thus, while traditional obstacle avoidance involves sensing obstacles using a variety of means, such as ultrasound or infra-red sensors, this technique uses a *mechanical* contact between object and sensor (i.e. the whisker). Varying the arrangement, stiffness and length of the whiskers would change the quality of performance in different tasks, such as wall-following or obstacle avoidance. Thus, the morphology of the whiskers directly affects the behaviour of the robot similar to how different algorithms would. Both the environment itself and the robot's whiskers dictate to a large degree *how* the robot will behave, thus offsetting the computational burden from the central controller to these two passive elements.

6. Morphological Computation in Haptic Displays

Haptic displays are considered crucial elements in *human-in-the-loop* control, such as teleoperation systems and surgical robots. The robot's tactile and kinesthetic perceptions must be vividly and precisely replicated on operator's side. In this review, we focus on haptic displays that can actively change their morphology in order to generate haptic sensations through contact with human fingers.

Morphological computation has benefited haptic devices with flexible structures that can actively vary their shape in order to transmit various tactile or kinesthetic perceptions such as contact state, stiffness and texture to human operators. Displaying the stiffness of the touched object, as well as other mechanical characteristics, has been widely studied recently due to the emerging need of haptic feedback in surgical tele-manipulators, especially in remote or automatic palpation [116]. In this task, localising a tumour underneath the skin requires a wide assessment of the surrounding tissue's stiffness/softness by measuring deformation and pressure distributions under an indention [117]. Therefore, the haptic sensation of different stiffness levels should be generated continuously. Authors in [118] proposed the design of a haptic device that could control its morphology, including mechanical properties (stiffness) and surface geometry (texture), through a combination of particle jamming and pneumatic actuation. This multi-cell device was filled with granular material on the 'skin layer', while an air chamber was situated below each cell. When applying a vacuum, each cell's skin could quickly turn from a soft state to a rigid state (or jammed state), thus flexibly controlling the stiffness of the device's surface. In addition, each cell could be inflated to different heights by applying compressed air into their respective chambers. The spatial resolution of the haptic display was proportional to the number of cells. As a result, the morphology of the surface, including its stiffness and shape, was entirely controlled. The authors also proposed a model for computation of the surface morphology and demonstrated the accuracy of the device in reproducing the haptic information sent (i.e. that it was *transparent*) [119]. Similar work combining jamming and pneumatics for controlling or simulating tissue palpation was proposed in [36,120]. Another review on changing stiffness of robotic systems can be found in [121].

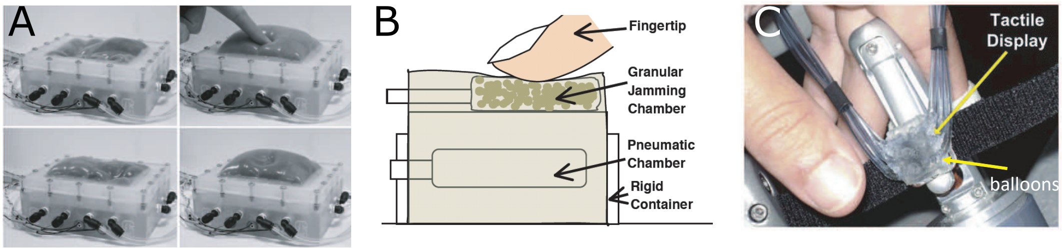

Figure 11. A representative haptic device for displaying tactile features which exploits its morphology to improve performance. (A) Haptic Jamming Surface (reproduced from [116]). (B) Granular jamming stiffness feedback actuators (reproduced from [36]). (C) Array of haptic balloons on display system (reproduced from [123]).

In order to display tissue characteristics such as texture or shape, arrays of balloons have been often utilised for controlling the morphology of structures [122]. The morphology and performance of soft dome arrays, including size, stiffness and resolution, were optimised to conform to the shape of a finger and generate enough force to replicate cutaneous tactile sensation [123,124]. As a result, differing to conventional rigid tactile displays that commonly use pins [125] or motorised moving surfaces [126], soft tactile displays tend to take advantage of the morphology of pneumatically-actuated domed or curved structures. As shown in Figure 9, this dome shape resembles the sensing organs of crocodiles and the star-nosed mole as discussed in Sections 3.2 and 3.4 and serves a similar function. That is, in crocodillian ISOs, the compliant dome morphology acts like a lens that focuses stimuli over a large area (the surface of the dome) onto a smaller area (the mechanoreceptor) and enables a more diffuse and efficient distribution of these receptors. In the case of tactile display, the dome structure acts in reverse: the stimulus originates from a small, discrete area at the centre of the dome (for example, the air inlet tube) and is diffused across the area of the dome's surface. This affords the tactile display system a similar advantage to that of ISOs, as fewer individual points of actuation are required to reproduce a continuous tactile feature. Furthermore, this selection of morphology in the haptic displays is useful as it is able to passively conform to the shape of the finger (unlike a rigid design).

7. Discussion

By reviewing the work in the previous sections, it has been the aim of this paper to demonstrate how morphological computation can be harnessed to great effect in tactile systems and haptics in general. It is the opinion of the authors, however, that much of the potential of morphological computational systems—especially in the context of soft robotics and haptics—remains largely unexplored. In this section, the potential for new haptic systems using morphological computation will be discussed as well as potential research avenues and design principles for realising this potential.

7.1 *Approaches to New Research*

In this work, passive and active morphological systems in haptics have been compared to traditional analogue/digital control system counterparts. In other words, as discussed in Sections 2 and 3, morphology can act as a *filter* or, put slightly differently, a *computational element*. Therefore, it is reasonable to assume that if a number of these elements are combined in a network, more complex behaviour could be achieved [127].

In the case where several morphological computing elements are combined, it is convenient to refer to the system as exhibiting morphological *processing*. In other words, the system is able to dynamically adjust its own behaviour in response to a wide range of stimuli without the need for additional controller supervision. This differs from active morphology in that instead of having an external controller or operator decide when to change the morphology of the system, for example making it stiffer, this 'decision' is taken by a secondary morphological element. This secondary element is designed such that it will send an appropriate signal, causing a change in the primary element's morphology. This, for instance, is similar to how humans do not consciously cause their fingers to wrinkle in water. This occurs due to the interaction of many different elements with different morphological properties.

A good example of a morphological processing system can be found in [128] where the soft-body dynamics of an octopus-inspired robotic tentacle were used to embed a kind of passive closed-loop control. Passive-dynamic walkers [5–10] also show that, by taking full advantage of a system's dynamics, complex gait and balancing can be achieved using simple controllers. The same underlying principle of taking advantage of morphology to create complex behaviour could be employed in haptics to create novel new systems. This could, for example, involve removing the need for controller supervision in any of the designs with active morphology mentioned in Section 4.2. That is, as opposed to requiring an external decision (from an operator or controller), a separate morphological element could compute the optimum morphological state and induce this change in the original element.

7.2 *Potential Topics of New Research*

Conceptually, this concept of complex morphological processing is not too difficult. In practice, however, it is difficult to realise. An extraordinary demand is placed on the designers' skill in materials selection and/or geometrical design. With regard to the materials selection, a possible approach could include examining materials which exhibit highly novel, non-linear (or downright strange) properties when exposed to certain stimuli. The authors speculate that these properties could be harnessed when designing new types of morphological computational element. A previous review has examined how some materials can be used to alter the stiffness of some structures [100], all of which are excellent candidates for such research. Furthermore, ref. [101] examines how soft robotics are being used to realise similar concepts.

In addition to this, there other physical phenomena which may be of interest for future research. Shear-thickening [129] and shear-thinning [130] fluids respectively increase or decrease their viscosity in proportion to the rate of shear. As a result, a morphological computation element could be designed around one of these fluids in order to change its stiffness and damping in response to different mechanical stimuli. Self-healing materials are able to fuse back together after breaking [131] and potentially recover properties such as conductivity [132]. Ferro-fluids are liquids which can be manipulated by magnetic fields [133,134]. Ferro-fluidic concepts already exist to use these novel properties to perform simple sorting tasks [134]. There are undoubtedly several other candidates, but those mentioned here are meant to merely illustrate the potential for new materials with novel properties. What all these materials all have in common is that their properties *naturally* change in some (semi) predictable way in response to certain stimuli. Were these changes in properties harnessed correctly, they could create sensors or robotic systems whose properties also naturally changed in response to stimuli without the need for controller supervision. The challenge is, of course, finding the right properties to change and then finding a material that exhibits such behaviour.

7.3 *Research Outlook*

While it is possible to identify material candidates for design of a true haptic morphological processing system, this does not make the actual task of designing the system any easier. In the field of haptics and morphological computation in general, there is a lack of general theory or set of best practices to guide such an endeavour. Zahedi et al. [135] tackled this problem using information theory. While excellent progress was made on *quantifying* morphological computation, there is still a gap between the immediate questions designers ask when building a system and the theoretical framework provided.

Any attempt at making a morphological processing system is instantly faced with a complex problem and few mathematical tools. Additionally, the very aspect of these materials which is so desirable is their inherent non-linearity. As a result, any attempt at defining a mathematical framework becomes significantly more challenging. Furthermore, when relying so heavily on the non-linear properties of materials, effects like creep, fatigue and other entropy-related phenomena may need to be considered, further complicating the issue. Complexity is therefore an inherent issue in any attempt at advanced morphological computation or processing.

On the other hand, the traditional approach of having a powerful, central control system that relies on precise models to plan complex actions is equally problematic, especially when replicating the haptic behaviours that come easily to some animals. In the opinion of the authors, while individual subsystems become more complex when using morphological computation, the overall complexity of system as a whole could potentially be reduced. Therefore, we propose a balanced approach where a certain amount of intelligence is embodied in the morphology of robots, reducing the need for the central controller supervision. This could potentially lead to systems which are capable of highly complex behaviours and interactions—thanks to their morphology—and are able to plan ahead more confidently—thanks to the reduced load on their controllers.

Morphological computation systems of increasing complexity should therefore be studied. Some general suggestions have been provided here for potential avenues for future work. Given the general lack of a guiding framework, however, we believe that there should be a focus on the production of prototypes. This will generate real data and provide a relatively new field with much needed practical experience.

8. Conclusion

In summary, this review has examined how the morphologies of some animals' tactile organs enable them to accomplish complex tactile tasks and interactions. Similar design principles have been shown to improve the performance of haptic displays, sensors and robotic systems. This involves the adept choice of environmental interaction strategies, geometries and material properties. Active techniques for controlling all of these design aspects can also greatly increase the range of behaviour a system is able to exhibit. Potential approaches to research have been suggested, including some non-linear materials which could lead to novel designs. Finally, the practicality of using morphological computation as a core design principle was considered.

In conclusion, embodying intelligence in passive components used for haptic systems allows them to passively regulate their own low-level haptic interactions with the environment. As a result, the computational burden is offset from the central controller, allowing it to focus more on high-level planning. This could create systems capable of more complex haptic behaviour in comparison to similar systems that rely on centralised control. Future research could potentially focus on placing morphological computation elements in a network to create more complex haptic behaviour without the need for controller supervision. While these individual morphological computation components may be more complex to design, on balance, the overall system architecture could potentially be simplified. In the process, it is also likely that a more general theory of design can be established, which is currently lacking in the context of morphological computation in haptics, further simplifying the design process. Morphological computation as a design principle in haptics has the potential to create systems capable of highly complex haptic interactions and behaviours beyond the reach of the current state of the art.

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